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# ELP-OA: Measuring the wave front tilt without a natural guide star

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## ABSTRACT

We describe the current status of the ELP-OA project in which we try to demonstrate in practice that it is possible to measure the tilt of a wave front using only a polychromatic laser guide star and no natural guide star. The first phase of ELP-OA, consisting of feasibility experiments, has recently been completed successfully. This paper provides an overview over the results of this first phase and over the continuation of the ELP-OA project.

## 1. INTRODUCTION

In this paper, we present a progress report of the project Étoile Laser Polychromatique et Optique Adaptative (ELP-OA). ELP-OA was created to demonstrate the feasibility of wave front tilt measurements with astronomical adaptive optics systems without the use of a natural guide star. Adaptive optics at astronomical telescopes aims at correcting the phase distortions of incoming wave fronts that are caused by the turbulent atmosphere in real time.[1] Measuring these distortions requires a bright source, called a guide star, within a small distance, the isoplanatic angle, from the science object. Usually, a natural star is used as this reference source and is then called a natural guide star (NGS). However, at visible wavelengths only a small fraction of the sky can be observed using a NGS, because the number of sufficiently bright stars in the sky is much smaller than what is necessary for complete sky coverage.[2] Unfortunately, this is the wavelength regime in which an adaptive optics system would be most useful, as the effect of atmospheric turbulence is the most detrimental for the resolution of large telescopes. Foy and Labeyrie[3] proposed a solution to overcome this difficulty by creating an artificial point source in the sky by emitting a laser in the direction of the observation. Depending on the type of the laser, light is backscattered from certain atmospheric layers, thus creating the artificial source, the laser guide star (LGS). Using an LGS produces a new problem, the insensitivity of the LGS to the overall tilt of the wave front. Because the round trip time of the laser beam to the atmospheric layers where the LGS is formed is significantly shorter than the typical tilt coherence time,[4] the backscattered light follows the

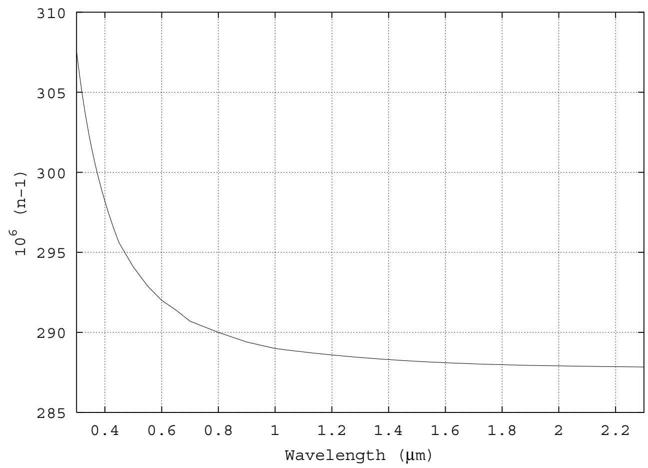


**Figure 1.** Variation of the index of refraction of air with wavelength

same path as the laser beam. The apparent direction of the LGS is therefore independent from the tilt and the tilt cannot be measured.

The "classical" way to overcome the tilt indetermination problem of LGSs is to use an NGS additional to the LGS.[5–7] It was first expected that a dimmer star can then be used for the tilt measurement than what is necessary for measuring all orders of the wave front distortions. It was shown, however, that this is not possible because correcting the tilt requires a higher measurement accuracy for the higher orders of the wave front, if comparable Strehl ratios are to be achieved.[8] Hence, current adaptive optics devices coupled with LGSs face low sky coverage problems in a similar way as all-NGS adaptive optics systems.[9,2] Several methods have been proposed to increase the sky coverage for LGSs, such as the dual adaptive optics concept,[8] the elongation perspective method,[10,11] and the polychromatic LGS (hereafter referred to as PLGS).[12,13] If one of these methods can be shown to be applicable at an astronomical site, the number of observable astronomical objects can be increased significantly for observations at visible wavelengths and in some cases, for example for the PLGS, a total independence from NGSs and 100% sky coverage can be reached. The feasibility of the methods listed above is therefore of great importance for today's astronomical research. The ELP-OA project was thus created to investigate the feasibility of using a PLGS at an astronomical telescope site. In this paper, we present the current status report of ELP-OA.

## 2. PRINCIPLE OF THE PLGS

A PLGS is a laser guide star that emits light at different wavelengths. The concept of the PLGS is based on the chromatic properties of the refractive index of air, $n$. Figure 1 shows how $n$ varies with wavelength from the near ultraviolet to the near infrared. Light of different wavelengths is refracted differently by the turbulent atmosphere. The light that is backscattered from a PLGS therefore crosses the atmosphere through different optical paths at different wavelengths resulting in a different tilt for each wavelength. The angular distance between the tilts at two wavelengths is the differential tilt, $\Delta\theta$, which is related to the tilt, $\theta$, through

$$\Delta\theta = \theta \frac{\Delta n}{(n-1)}, \tag{1}$$

where $\Delta n$ stands for the variation of $n$ over the wavelength baseline of the monochromatic components used for the differential tilt measurements.[13] In theory, the tilt can therefore be calculated from the measurable differential tilt.

While the variation of the refractive index with wavelength is small in general, it is larger at ultraviolet than at visible and infrared wavelengths. It is therefore advantageous to use an excitation process of atmospheric molecules or atoms that produces light at at least one ultraviolet wavelength. Such a process is the excitation of mesospheric sodium atoms into the $4D_{5/2}$ energy level, from which the radiative decay back to the ground level produces a line spectrum spanning the wavelength interval from 330 nm to 2.3 $\mu$m. A two-photon coherent absorption through the $3P_{3/2}$ energy level (589 and 569 nm) allows us to reach this energy level. Foy et al.[13] have shown this excitation to be one of the most promising for the implementation of a PLGS system and most of ELP-OA concentrates thereon.

The factor $\Delta n/(n-1)$ in Eq. (1) is much smaller than unity for the wavelengths of interest for astronomical adaptive optics. It is therefore obvious that a very high precision of the differential tilt measurement is necessary in order for the PLGS concept to be applicable in practice. The ELP-OA project was created to investigate the applicability of the PLGs at astronomical sites. Several key factors for a PLGS system were investigated experimentally during the feasibility study phase of ELP-OA (hereafter simply referred to as "Phase 1"), for example, the return flux from the PLGS (of special importance is the return flux at 330 nm),[13] telescope vibrations, and the accuracy of the tilt measurements. Phase 1 also included atomic physics models of the sodium atom, an end-to-end model of the proposed system, and research and development of dedicated lasers to determine the best possible configuration for "Phase 2" of ELP-OA. The goal of Phase 2 is to build a PLGS system coupled with the adaptive optics device BOA developed by ONERA[14] at the 1.52-m telescope of the Observatoire de Haute-Provence (OHP) and to observe long-exposure diffraction limited images without any natural reference source. In the following sections, we present results we have obtained by the end of Phase 1 in December 1999 as well as an introduction to Phase 2.

## 3. RETURN FLUX AT 330 NM: THE PASS-2 EXPERIMENT

Since the tilt is derived from a differential measurement in the PLGs method, significantly higher precision and thus higher return fluxes are required to determine the positions of the monochromatic components of the PLGS than to find the tilt from a natural guide star. This is particularly important for the 330 nm component, as has been shown by Foy et al.[13] We had carried out a first experiment, called Polychromatic Artificial Star System (hereafter referred to as PASS-1), to measure the return flux at 330 nm at the Lawrence Livermore National Laboratory (LLNL) in collaboration with the AVLIS (Atomic Vapor Laser Isotope Separation) team.[15] The average laser power of the copper vapor lasers used was approximately 180 W for each of the beams (569 and 589 nm) at pulse repetition rates of 4.3 and 12.9 kHz, pulse durations (FWHM) of 50 ns, and modulation widths of 3 GHz at 589 nm and 1 GHz at 569 nm. Unfortunately, poor weather conditions prevented us from making all measurements necessary for the unambiguous interpretation of the data. Additionally, preliminary computations of sodium atom models predicted return fluxes significantly lower than those observed at the LLNL. Thus, a second experimental campaign, the PASS-2 experiment, was carried out at the Commissariat à l'Énergie Atomique (CEA) in collaboration with the SILVA (Séparation isotopique par laser à vapeur atomique) team at its Pierrelatte site. The observations were performed during 6 weeks in October and November of 1999.

An in-depth description and discussion of the PASS-2 setup is given by Schöck et al.[16] An overview over the experimental setup is shown in Fig. 2. The laser beams (parameters of the laser chain are given in Table 1) are emitted via a small telescope. An identical telescope is then used to observe the light that is backscattered from the mesospheric sodium layer. To aid with the interpretation of the data, we also operated a turbulence monitor and a sodium density monitor simultaneously with the laser emission and reception telescopes.

**Table 1.** Principal characteristics of the laser configuration.

| | |
|---|---|
| Total power in both colors | 10 – 100 W |
| Ratio of the powers in the two colors | 1:1 |
| Pulse repetition rate | 5 kHz |
| Beam polarization | linear |
| Modulation | one modulator, 180 MHz at 589 nm, 125 MHz at 569 nm, or 2 modulators, 180 MHz and 300 MHz, at 589 nm broadened to $\approx 0.5$ GHz |
| Spectral characteristics | linewidth: 50 MHz spectral jitter: 100 MHz |
| Pulse shape | triangular |
| Pulse duration | 35 ns at FWHM, 70 ns at the base |
| Wave front quality | better than $1\lambda$ |
| Beam diameter | $28 \times 34$ mm$^2$ |
| Precision of beam superposition | better than 10% of the diffraction limit |

Two series of measurements of the return flux at 330 nm were performed with two different oscillators. The first oscillator was the original SILVA oscillator with different modulation configurations: no modulation, a single sine

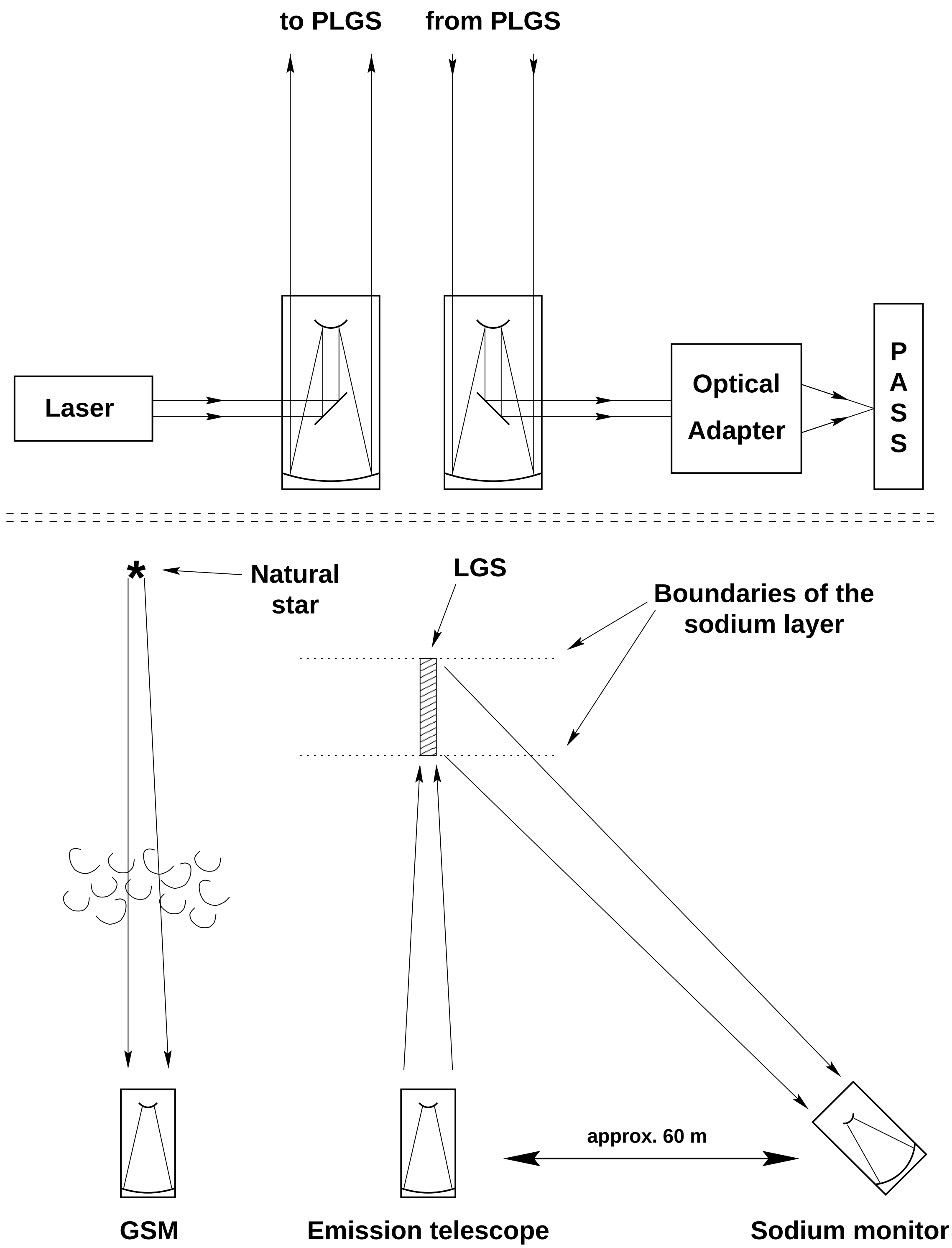


**Figure 2.** Schematic of the setup of the PASS-2 experiment. Top: the emission and reception system. Bottom: the auxiliary systems: Generalized Seeing Monitor (GSM) and sodium monitor. PLGS = polychromatic laser guide star.

modulation (at 180 MHz), or a two-sine modulation (at 180 and 300 MHz) for the 589 nm beam and a single sine modulation (at 125 MHz) for the 569 nm beam. In both the last cases, the modulation width was approximately 0.5 GHz. Return fluxes measured with the SILVA oscillators are shown in Fig. 3. The results can be shown to be consistent with the measurements taken at the LLNL, thus confirming the validity of the PASS-1 results. Agreement with theoretical results has now also been reached.

The second type of oscillator, which is a laser with a particularly low spectral jitter ($\leq 1$ MHz), was developed by the Laboratoire de Spectrométrie Physique (LSP). This type of laser was used to investigate the effect of the laser jitter on the return flux from the PLGS. The laser spectrum, even with modulation, is far from filling the entire Doppler spectrum of mesospheric sodium, the ideal case in which all sodium atoms can be excited. In spite, the modulation function of the laser spectral profile contains several strong but narrow spikes separated by large gaps, at least as long as the Rabi frequency, which widens the spikes, is smaller than these gap. Thus, it is necessary that the modulation functions of both beams used for creating the PLGS are identical. If this is not the case, atoms excited by the 589 nm beam to the $3P_{3/2}$ energy level may be not excited to the $4D_{5/2}$ level by the 569 nm beam and a significant loss of return flux with respect to the optimal case can appear.

Spectral jitter of the lasers causes randomly variable shift of the beam spectral profile. This shift is different for the two laser beams. The oscillator of the SILVA chain has a spectral jitter width of approximately 100 MHz, which is much larger than the homogeneous line width of sodium (10 and 13 MHz at 589 and 569 nm, respectively). At the highest peak powers used in PASS-2 this jitter is small compared to the Rabi frequency and can be ignored. However, at low values of the peak power, the Rabi frequency is small and the efficiency of the two-color excitation process drops significantly. Because we have to decrease the average laser power as much as possible for astronomical applications of the PLGS, spectral jitter is a major concern and its effect was therefore investigated during the PASS-2 experiment, although a lack of time and bad weather prevented us from making all the desired measurements. Preliminary results of the return flux obtained using the LSP oscillators are given in Fig. 4. Full results will be available and published shortly. As with the SILVA oscillators, the results have been shown to be in agreement with theoretical models.

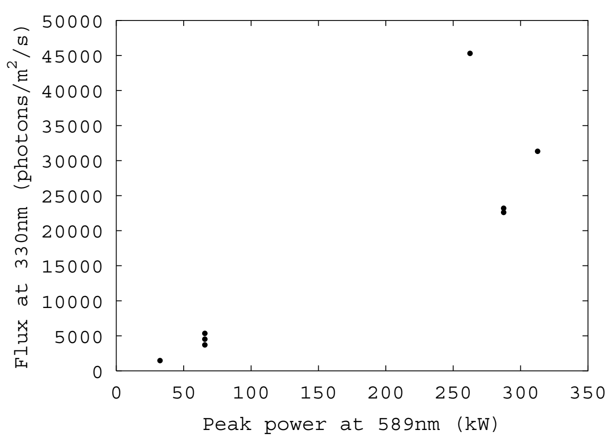


**Figure 3.** Return flux at 330 nm as a function of the laser peak power at 589 nm. These preliminary measurements were taken using the CEA oscillator. The values shown apply to an atmospheric and instrument transmission of unity.

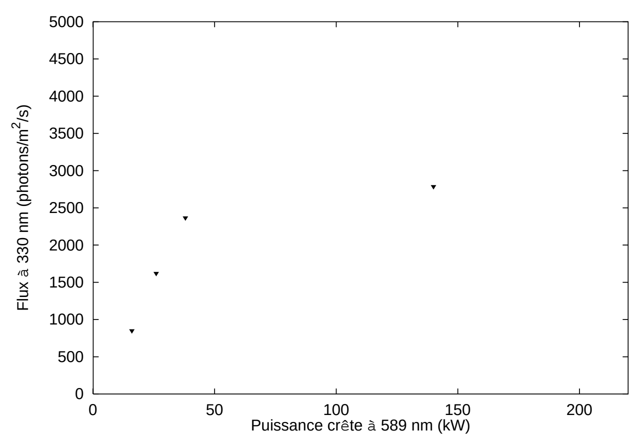


**Figure 4.** Return flux at 330 nm as a function of the laser peak power at 589 nm. These measurements were taken using the the low-jitter oscillator of the LSP without frequency modulation. The values shown apply to an atmospheric and instrument transmission of unity.

In the case of PASS-2, we were able to run two auxiliary experiments simultaneously with the photometry measurements. The first one had the purpose of measuring the sodium column density. The second experiment was the Generalized Seeing Monitor (GSM)[17] which we borrowed from the Université de Nice-Sophia-Antipolis. With the GSM, we measured Fried's parameter, $r_0$, as well as fluctuations of the atmospheric transparency. The seeing conditions were quite poor, as expected during the fall in France and basically at sea level. On average, we found $r_0 \approx$ 4 cm. The results from the auxiliary experiments are used to take sodium density and seeing variations into account that occurred during the campaign from night to night or even within the same night. More detailed descriptions of the setups are given by Schöck et al.[16]

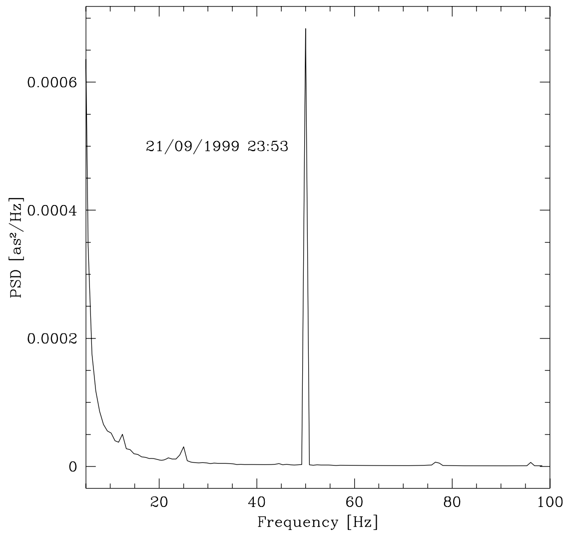


**Figure 5.** Vibrations at the Observatoire de Haute-Provence 1.52-m telescope, right ascension axis, telescope tracking on, dome open. Data sampling: 200 Hz. The low frequency domain of the power spectrum is not displayed, because of the strong contribution of the atmospheric tilt. The 6 mas amplitude peak at 50 Hz is due to an electronic parasite. The amplitude of the peak at 76 Hz is lower than 2 marcsec.

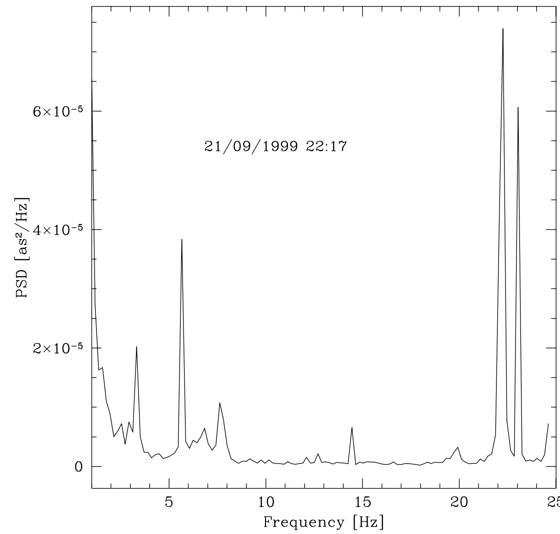


**Figure 6.** Vibrations at the Observatoire de Haute-Provence 1.52-m telescope, declination axis, telescope tracking on, dome open.

## 4. TELESCOPE VIBRATIONS: THE PENDULAR SEISMOMETER

Since the concept of the PLGS relies on the chromatic differences of the refractive index of air, it does not permit us to correct for the mechanical causes of the image wandering at the telescope focus such as telescope vibrations. Such vibrations are not negligible when compared with the telescope diffraction limit.[18–21] At $H_\alpha$ and an 8 m telescope, an acceptable degradation of the Strehl ratio by a factor of 0.8 rms is found for a mechanical tilt of 7.0 marcsec. Assuming monochromatic sinusoidal vibrations at 1 Hz, the angular acceleration is then 1.8 $10^{-6}$s$^{-2}$, and the linear acceleration is 7 $10^{-7}$g (7 $10^{-9}$g at 0.1 Hz).

Laser gyroscopes[22,23] have performances which are not adequate. Accelerometers have been used, for instance at ESO, to measure telescope vibrations.[24,25] However, the best accelerometer resolution is approximately $10^{-6}$g, which provides the adequate sensitivity only in the high frequency domain. Hence, a special instrument has been conceived and built at the Observatoire de Lyon to span the frequency range from 0.1 to approximately 30 Hz. It is a new kind of seismometer, a pendular seismometer.[26,27] While seismometer used in geophysical studies sense either horizontal or vertical translations, the pendular seismometer senses angular displacements. In preparation for Phase 2 of ELP-OA, we have measured the vibration properties of the 1.52-m telescope at the OHP with the pendular seismometer. Figures 5 and 6 show that they lie within the range of the usual tip-tilt mirror specifications. After filtering of two components of the power spectrum at 5 kHz and 650 Hz, the measured rms noise of the pendular seismometer is 3 marcsec in the 0-25 Hz band. Thus, the prototype instrument already matches the specifications for diffraction-limited imaging at 8-10 m class telescopes.

## 5. ACCURACY OF MEASUREMENTS: THE MATILD EXPERIMENT

The magnitude of the differential tilt is approximately 1/20 of the magnitude of the tilt for the wavelengths of interest for ELP-OA [Eq. (1)]. Thus, measuring the tilt at an accuracy of a fraction of the Airy disk from the differential tilt requires measurement accuracies of the order of 1 milliarcsecond. Since this is not trivial, we have carried out the

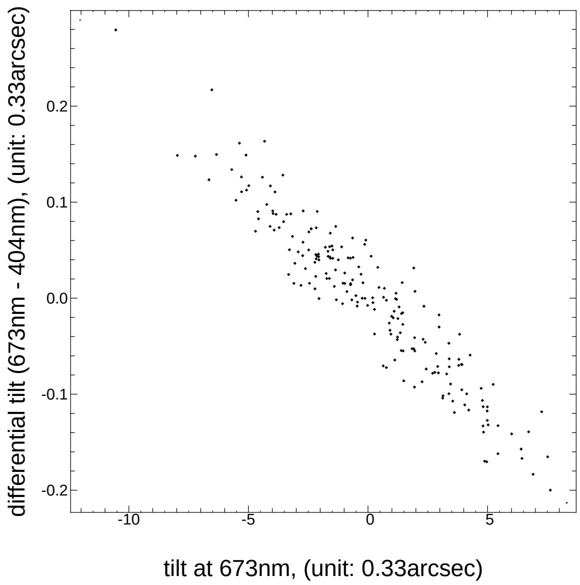


**Figure 7.** Correlation between differential tilt (673nm-404nm) and tilt (at 673nm) using the center of gravity method. This correlation is obtained by using 200 simulations of MaTilD-like images, including all the noise sources studied.

MaTilD (Manipulation de Tilt Différentiel) experiment.[28] It aims at testing whether this accuracy is achievable in conditions as realistic as possible. A multi-wavelength (from 300 to 673 nm) point source is generated and the beams are propagated horizontally over approximately 100 m at an altitude varying from 3 to 16 m above the ground at night time. Data have first been simulated to evaluate the sources of noise and bias (photon noise, speckle noise, dark current, readout noise, slight overlapping of the monochromatic images). Figure 7 shows the correlation between the tilt and the tilt measured from the differential tilt over a limited spectral basis, obtained from simulated data including all the identified sources of noise.

Additionally to using a simple center-of-gravity method to determine the wave-front tilt, a phase mapping algorithm has been written to measure the differential tilt. First estimates promise a significant increase of tilt determination accuracy. They seem to indicate that the rms error could be smaller than that obtained with the center-of-gravity algorithm by a factor 3 to 10 for typical values of $10^6$ to $10^4$ photons per image.[28]

## 6. SODIUM ATOM MODELS: BACON CODE AND KINETICS EQUATION MODEL

The code *Bacon* has been developed for the ELP-OA project. The goal of this code is to find the maximum of the fluorescence photon flux (at 330 nm) as a function of the laser excitation parameters (fluence, pulse duration, phase modulation parameters, etc.). A density matrix formalism has been used to solve the 48 equations of the two-step excitation process of the sodium atom considering the following energy levels: $S_{\frac{1}{2}} : F \in [1, 2]; 3P_{\frac{3}{2}} : F \in [0, 3]; 4D_{\frac{5}{2}} : F \in [1, 4]; 4P_{\frac{3}{2}} : F \in [0; 3];$ and $4S_{\frac{1}{2}} : F \in [1, 2]$; and for each $F, M_F \in [-F, F]$). The $4D_{3/2}$ level has been neglected in the excitation ladder. The Doppler line profiles have been divided into several classes and the equations are solved for each class. The laser fields can be mono-mode or phase-modulated with different temporal shapes and different light polarizations. At the end, the populations of the considered levels and the number of photons emitted at 589, 569 and 330 nm are given as output. Results of this code have been compared with those of Morris[29] for a one-step excitation as well as with experiments. Predicted return fluxes at 330 and 589 nm are shown in Figs. 8 and 9. At the average power $< P >= 55$ W and with a single-sine modulation, the intensity at Pierrelatte was approximately

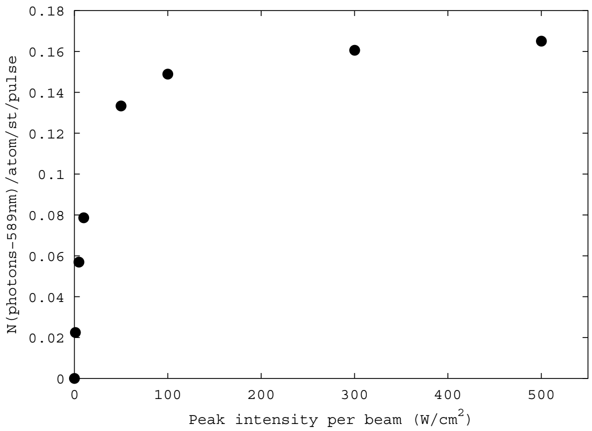


**Figure 8.** Predicted return flux at 589 nm versus the peak power per beam.

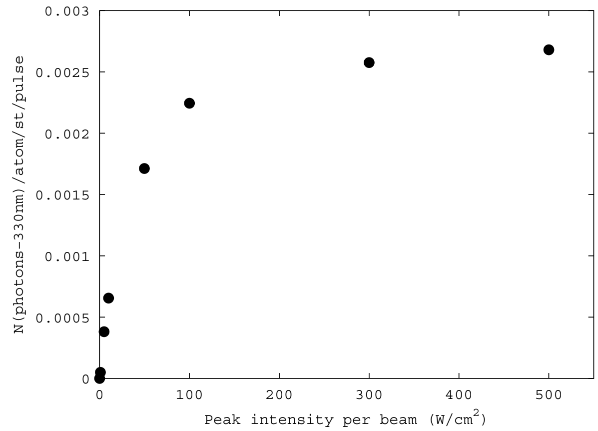


**Figure 9.** Predicted return flux at 330 nm versus the peak power per beam.

9 W cm$^{-2}$. Then, according to the figures the absorption at the sodium layer was saturated. Given an average laser power, a lower peak power and a higher pulse repetition rate would therefore lead to higher return fluxes.

Because of the large number of sub-levels taken into account in the density matrix code and in the sampling of the Doppler line profiles, computation times for a single parameter configuration are large. We have therefore also developed a much faster code based on kinetics equations. We have calibrated these kinetics equations code by means of the Bacon code. It can thus be used if immediate but less precise results are needed.

## 7. AN END-TO-END PERFORMANCE MODEL

All the results from Phase 1 of ELP-OA are combined in an end-to-end theoretical model, hereafter simply referred to as the "budget link". We had two main reasons to develop this budget link. First, it is indispensable for the design study for Phase 2 of ELP-OA in order to make ELP-OA a meaningful feasibility experiment for astronomical PLGS systems. Second, it can also be used to predict the performance of PLGS adaptive optics systems at large astronomical telescope sites. A detailed description of the budget link together with performance predictions for ELP-OA and PLGS systems at 8-m class telescopes is almost finished at this time and will be available shortly. Here, we have only space to present a few selected assumptions and results.

The goal of the budget link is to estimate the expected performance of a tilt correction system that is based on a PLGS. Only errors caused by the tilt or the tilt system are therefore considered. The Strehl ratio of the tilt correction system is used as a measure of its performance. If no other errors are present, the tilt Strehl ratio, $S_{tilt}$, of an image depends on the variance of the tilt measurement, $\sigma^2_{tilt}$ as[30]

$$S_{tilt} = \frac{1}{1 + \frac{\pi^2}{2}\sigma^2_{tilt}\left(\frac{D_r}{\lambda_c}\right)^2}, \tag{2}$$

where $\lambda_c$ is the wavelength at which the wave front is corrected and $D_r$ is the diameter of the reception telescope. Equation 2 is obtained by fitting a Gaussian to the theoretical shape (Airi disk) of the spot in the mesosphere. The tilt and thus $\sigma^2_{tilt}$ are understood to be in angular units. We note that $\lambda_c$ is generally not identical with any of the two wavelengths used for the tilt determination.

The error of the tilt system is given by

$$\sigma^2_{tilt} = \sigma^2_{ph} + \sigma^2_{bw} + \sigma^2_{instr} + \sigma^2_{cone} + \sigma^2_{halo}, \tag{3}$$

where the dominant error sources are the tilt measurement error (photon noise), $\sigma^2_{ph}$, and the tilt bandwidth error (caused by the finite integration time), $\sigma^2_{bw}$. These two errors are treated in detail in the budget link.

$\sigma_{instr}$ in Eq. (3) describes the sum of all instrumental errors. These errors consist primarily of the readout noise and the dark current of the detector. Because of the nature of the PLGS tilt determination process, we are dealing with exposure times of tens of milliseconds and are working in a high-photon regime. Thus, we assume that, when working with a good detector, we can neglect both readout noise and dark current in the treatment presented here. [We note that the center-of-gravity method of the tilt determination has a higher precision if a larger part of the detector, that is, more pixels are used. The readout noise, however, increases also with the numbers of pixels. It is thus clear that, for a specific system, a compromise between these two competing effects has to be found.] We further make the assumption that no instrumental biases exist. Thus, we assume that we can neglect $\sigma^2_{instr}$ with respect to the dominant error sources.

The fourth term in Eq. (3), $\sigma^2_{cone}$, is the error caused by the cone effect of the tilt measurement. For ELP-OA, using a 1.52-m telescope, the cone effect is small and can be neglected. For an 8-m-class telescope, a single laser guide star produces non-acceptable wave-front corrections due to the cone effect even if the tilt is measured with an NGS. We therefore assume that the PLGS will be implemented at a large telescope only in combination with a multi-conjugate adaptive optics (MCAO) system. It has been shown[31] that it is sufficient to measure the absolute tilt with only one of the guide stars in order to determine the entire wave front distortion, including the tilt. We therefore assume that we will be working with an MCAO system consisting only of LGSs, one of which is a PLGS. There will then be no significant contribution of $\sigma^2_{cone}$ to the error budget.

The last source of error, $\sigma^2_{halo}$, is caused by the seeing-limited halo of the laser spot in the mesosphere (we assume emission of the laser beams with an adaptive optics system). Because of this halo, there are photons arriving at the reception telescope from outside the diffraction-limited core of the PLGS that is used as the tilt guide star. Here, we are only interested in systems that produce a very high Strehl ratio of the emission system. We can therefore assume that virtually all photons come from the core of the mesospheric laser spot and that we can neglect $\sigma^2_{halo}$. In the budget link, we nevertheless set up the equations for $\sigma^2_{halo}$.

With the assumptions made above, the total tilt error is now given by $\sigma^2_{tilt} = \sigma^2_{ph} + \sigma^2_{bw}$. We can then show that the Strehl ratio of the tilt correction system is given by

$$S_{tilt} = \frac{1}{1 + \left(\frac{n-1}{\Delta n}\right)^2 \frac{2.34\lambda_e^2}{\eta \Phi_P D_e^2 \lambda_c^2 t_i} + \frac{2\pi^4}{\sqrt{12}} f_T^2 t_i^2} \tag{4}$$

and that this Strehl ratio is obtained at an optimum integration time

$$t_i = 0.28 \left[ \left(\frac{n-1}{\Delta n}\right)^2 \frac{\lambda_e^2}{\eta \Phi_P D_e^2 \lambda_c^2 f_T^2} \right]^{1/3} . \tag{5}$$

Here, $\lambda_e$ is the wavelength of the laser emission system, $\eta$ is the combined transparency of the atmosphere and the reception system at 330 nm, $\Phi_P$ is the photon return flux at 330 nm, $D_e$ is the diameter of the emission telescope, and $f_T$ is the tilt coherence frequency.

We conclude this section with a few physical interpretations of Eqs. (4) and (5). We first point out that $f_T \propto \lambda_c^{-1}$ (see Tyler 1994)[32] and that $t_i$ does therefore not depend on the wavelength of observation. This independence originates from the fact that we are working with the tilt in units of angle of arrival of the wave front, which is independent of the correction wavelength, $\lambda_c$. Nevertheless and as expected, both error terms in Eq. (4) depend on $\lambda_c$ in such a way that a higher Strehl ratio is reached at longer wavelengths.

We also find that the tilt measurement error, $\sigma^2_{ph}$, does not depend on $D_r$. While more photons are collected with a larger reception telescope, the precision needed in the differential tilt determination also increases with $D_r$. This result is in accordance with and explained by Foy et al.[13] A slight dependence on $D_r$, favoring large telescopes, enters Eq. (4) through $f_T$.

For constant laser intensity in the spot, the return flux, $\Phi_P$, is directly proportional to the area of the laser spot in the mesosphere, which is proportional to $D_e^{-2}$. Thus, for a constant intensity, $S_{tilt}$ does not depend on the size of the laser spot in the mesosphere. However, if the spot size is decreased, the intensity in the spot and with it the return flux per spot area (or the "brightness" of the PLGS) increases. This increase in return flux is linear with intensity before saturation of the sodium transitions and smaller than linear for laser intensities higher than saturation. Thus, the Strehl ratio of the tilt measurement will increase with decreasing spot size in the mesosphere. It is therefore desirable to produce the smallest possible laser spot in the mesosphere, favoring a large emission telescope with an AO system.

In summary, we have shown that the performance of a tilt correction system with a PLGS improves with increasing diameters of both the emission and the reception telescopes and that an AO system for the emission telescope is desirable. [It is clear, that a compromise between increased performance on one side and system cost and saturation effects on the other side needs to be found.] It should be obvious that increasing the return flux from the PLGS, for example by increasing the laser power or the duty cycle, and increasing the magnitude of the dispersion effect by using a larger difference between the wavelengths of the two lasers also increases the performance. These two effects are represented in Eq. (4) by the dependence of $S_{tilt}$ on $\Phi_P$ and $\Delta n$. Finally and as always, the quality of the atmospheric conditions of the site, that is, the magnitude of the tilt coherence frequency, $f_T$, has a large influence on the Strehl ratio achieved by the system.

Examples of the application of the budget link are presented in Figures 10 and 11. The figures show the numbers of photons necessary per tilt measurement (for one possible ELP-OA configuration and an 8-m class telescope at an astronomical site) to reach a certain Strehl ratio for different wavelengths and different atmospheric conditions.

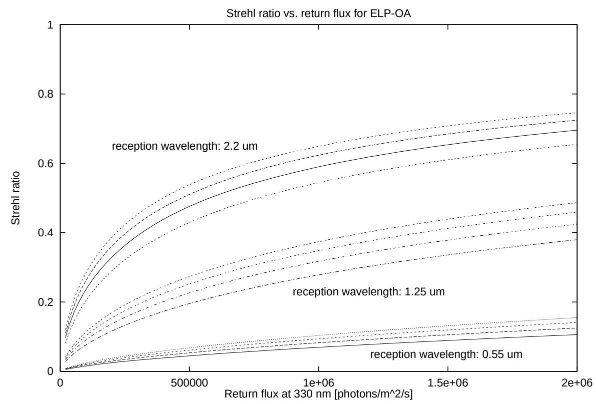


**Figure 10.** Strehl ratio vs. return flux at 330 nm, $\Phi_P$, for a non-optimized configuration of ELP-OA. The set of 4 curves with the highest values is calculated for tilt correction in the K band (2.2 $\mu$m), the middle set is for the J band (1.25 $\mu$m), and the bottom set is for the V band (0.55 $\mu$). The 4 curves in each set correspond to different values of $r_0$: 5 cm (bottom curve of each set), 7 cm, 9 cm, and 11 cm (top curve of each set). The return flux used is normalized to an atmospheric and instrument transmission $\eta = 1$.

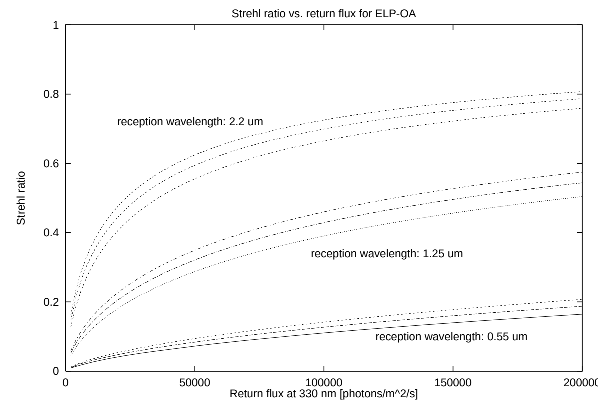


**Figure 11.** Strehl ratio vs. return flux at 330 nm, $\Phi_P$, for a possible configuration at an 8-m telescope. The set of 3 curves with the highest values is calculated for tilt correction in the K band (2.2 $\mu$m), the middle set is for the J band (1.25 $\mu$m), and the bottom set is for the V band (0.55 $\mu$). The 3 curves in each set correspond to different values of $r_0$: 15 cm (bottom curve of each set), 20 cm, and 25 cm (top curve of each set). The return flux used is normalized to an atmospheric and instrument transmission $\eta = 1$.

## 8. CONCLUSIONS

The feasibility phase of the ELP-OA project has been completed successfully. We have now available all the information and tools that are necessary for the design and implementation phase (Phase 2) of the project. The next step is to set up an experiment at the 1.52-m telescope of Observatoire de Haute Provence (southern France) where an adaptive optics system will be fed with a polychromatic laser guide star in order to obtain long-exposure diffraction-limited images without any natural guide star. The expected time for Phase 2 of the ELP-OA program is three years. With the budget link presented in parts in this paper, it is also possible to calculate the expected performance of a PLGS system at a large telescope at a good astronomical site.

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## REFERENCES


1. H. W. Babcock, "The possibility of compensating astronomical seeing," *PASP* **65**, p. 229, 1953.
2. M. Le Louarn, R. Foy, N. Hubin, and M. Tallon, "Laser guide star for 3.6m and 8m telescopes: Performances and astrophysical implications," *Mon. Not. R. astron. Soc* **295**, pp. 756–768, 1998.
3. R. Foy and A. Labeyrie, "Feasibility of adaptive telescope with laser probe," *AA* **152**, pp. L29–32, 1985.
4. J. Pilkington, "Artificial guide stars for adaptive imaging," *Nature* **330**, p. 116, 1987.
5. R. Davies, W. Hackenberg, T. Ott, A. Eckart, S. Rabien, S. Anders, S. Hippler, M. Kasper, P. Kalas, A. Quirrenbach, and A. Glindemann, "The science potential of ALFA: Adaptive optics with natural and laser guide stars," *Astron. Astrophys. Suppl. Ser.* **138**, pp. 345–353, 1999.
6. S. S. Olivier, D. T. Gavel, H. W. Friedman, C. E. Max, J. R. An, K. Avicola, B. Bauman, J. M. Brase, E. Campbell, C. Carrano, J. Cooke, G. Freeze, E. Gates, V. Kanz, K. T, C, B. Macintosh, M. Newman, E. Pierce, K. Waltjen, and J. Watson, "Improved performances of the laser guide star adaptive optics at Lick observatory," in *Adaptive optics systems and technology*, R. K. Tyson and R. Q. Fugate, eds., vol. 3762 of *Proc. SPIE*, 1999.
7. J. Sebag, C. d'Orgeville, M. Chun, J. Filhaber, J. Oschmann, F. Rigaut, and D. Simons, "Lick sodium laser guide star: performance during 1998 LGS observing campaign," in *Adaptive optics systems and technology*, R. K. Tyson and R. Q. Fugate, eds., vol. 3762 of *Proc. SPIE*, 1999.
8. F. Rigaut and E. Gendron, "Laser guide star in adaptive optics: the tilt determination problem," *Astron. Astrophys.* **261**, pp. 677–684, 1992.
9. S. Olivier, C. Max, D. T. Gavel, and M. J. Brase, "Tip-tilt compensation - resolution limits for ground-based telescopes using laser guide star adaptive optics," *Astrophys. J.* **407**, pp. 428–439, 1993.
10. R. Ragazzoni, "Robust tilt determination from laser guide star using a combination of different techniques," *Astron. Astrophys.* **319**, pp. L9–L12, 1997.
11. M. Belenkii, S. J. Karis, J. M. B. II, and R. Q. Fugate, "Experimental validation of a technique to measure tilt from a laser guide star," *Opt. Lett.* **24**, pp. 637–639, 1999.
12. R. Foy, Y. Boucher, B. Fleury, G. Grynberg, P. R. McCullough, A. Migus, and M. Tallon, "ATLAS status report and tilt sensing using multicolour laser reference star," in *Progress in telescope and instrumentation technologies*, U. M.-H., ed., no. 42 in ESO conferences, pp. 437–441, ESO, (Garching, Germany), 1992.
13. R. Foy, A. Migus, F. Biraben, G. Grynberg, P. R. McCullough, and M. Tallon, "The polychromatic artificial sodium star: a new concept for correcting the atmospheric tilt," *AASup* **111**, pp. 569–578, 1995.
14. P.-Y. Madec, D. Rabaud, B. Fleury, J.-M. Conan, L.Rousset-Rouvière, F. Mendez, J. Montri, V. Michau, G. Rousset, and M. Séchaud, "Essais du banc d'optique adaptative ONERA à l'OHP," *La Lettre de l'OHP* **16**, pp. 2–3, 1997.
15. R. Foy, M. Tallon, E. Thiébaut, J. Vaillant, F.-C. Foy, D. Robert, H. Friedman, F. Biraben, G. Grynberg, J.-P. Gex, A. Mens, A. Migus, J.-M. Weulersse, and D. J. Butler, "Observation of a polychromatic laser guide star," *J. Opt. Soc. Am. A* **in press**, 2000.
16. M. Schöck, R. Foy, J.-P. Pique, P. Chevrou, N. Ageorges, A. Petit, V. Bellanger, H. Fews, F.-C. Foy, C. Högemann, M. Laubscher, O. Peillet, P. Segonds, M. Tallon, and J.-M. Weulersse, "PASS-2: Quantitative photometric measurements of the polychromatic laser guide star," in *Adaptive Optical Systems Technology*, vol. 4007 of *Proc. SPIE*, 2000.
17. J. Vernin and M. Azouit, "Traitement d'image adapté au speckle atmosphérique. II. Analyse multidimensionnelle appliquée au diagnostic à distance de la turbulence," *J. Optics (Paris)* **14**, pp. 131–142, 1983.

18. R. Foy, I. Belkine, and E. Thiébaut, "Pre-main sequence stars by visible speckle interferometry at the CFHT and telescope/instrument constraints," in *Proc. of the Canada-France-Hawaii-Telescope Users's meeting*, M. Azzopardi, ed., 4, pp. 119–123, CFHT, (Waimea, Hawaii), 1995.
19. E. Thiébaut, Y. Balega, I. Balega, I. Belkine, J. Bouvier, R. Foy, A. Blazit, and D. Bonneau, "Orbital motion of df tauri from speckle interferometry," *Astron. Astrophys. Lett.* **304**, pp. L17–L20, 1995.
20. E. J. Kibblewhite and M. R. Chun, "Design of tip-tilt and adaptive optics servos using measured angle-of-arrival and phase power spectra," in *Adaptive Optical System Technologies*, D. Bonaccini and R. K. Tyson, eds., vol. 3353 of *Proc. SPIE*, pp. 522–530, 1998.
21. S. Altarac, P. Berlioz-Arthaud, E. Thiébaut, and R. Foy, "Effect of telescope vibrations upon high angular resolution imaging," *Mon. Not. R. astron. Soc* **submitted**, 2000.
22. W. W. Chow, J. Gea-Banacloche, L. M. Pedrotti, V. E. Sanders, W. Schleich, and M. O. Scully, "The ring laser gyro," *Rev. Modern Phys.* **57**, pp. 61–104, 1985.
23. H. Dahlman, B. Huber, and W. Schröder, "Optical gyro encoder tested on the NTT," *The Messenger* **74**, pp. 5–6, 1993.
24. P. Bourlon, T. Ducros, and M. Faucherre, "Results of vibrations measurements on La Silla," in *High-resolution imaging by interferometry II*, J. M. Beckers and F. Merkle, eds., ESO Conferences, pp. 1215–1225, ESO, (Garching, Germany), 1991.
25. B. Koehler, "VLT unit telescope suitability for interfrometry: first results from acceptance tests on subsystems," in *SPIE*, 3350, 1998.
26. A. A. Tokovinin, "Pendular seismometer for compensating telescope vibrations," *Mon. Not. R. astron. Soc* **in press**, 2000.
27. A. A. Tokovinin, "Pendular seismometer for correcting telescope pointing errors," in *Adaptive Optical Systems Technology*, vol. 4007 of *Proc. SPIE*, 2000.
28. J. Vaillant, É. Thiébaut, and M. Tallon, "ELPOA: Data processing of chromatic differences of the tilt measured with a polychromatic laser guide star," in *Adaptive Optical Systems Technology*, vol. 4007 of *Proc. SPIE*, 2000.
29. J. Morris, "Efficient excitation of a mesospheric sodium laser guide starby intermediate-duration pulses," *J. Opt. Soc. Am. A* **11**, pp. 832–845, 1994.
30. D. G. Sandler, S. Stahl, J. Angel, M. Lloyd-Hart, and D. McCarthy, "Adaptive optics for diffraction-limited infrared imaging with 8-m telescopes," *J. Opt. Soc. Am. A* **11**, pp. 925–945, 1994.
31. R. Ragazzoni, S. Esposito, and A. Riccardi, "Multiple LGSs to correct conical anisokinetism.," *AASup* **128**, pp. 617–619, Mar. 1998.
32. G. Tyler, "Bandwidth considerations for tracking through turbulence," *J. Opt. Soc. Am. A* **11**, pp. 358–367, 1994.